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Intense storms in the Mediterranean: a first description from the ERA-40 perspective

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Abstract. The study of the Mediterranean cyclones from a climatological point of view has been one of the objectives of the first phase of WMO WWRP MEDEX (MEDiterranean EXperiment) project. It has been revealing itself like a good procedure for extracting conclusions about their characteristics and behaviour. The implementation on ECMWF ERA-40 reanalysis of the method for detecting and tracking the cyclones developed at the Centro Meteorológico Territorial (CMT) in Illes Balears of the Instituto Nacional de Meteorología (INM, Spain) has allowed the selection of the most intense storms occurred for the last 45 years. This selection has been based on the value of the cyclones' circulation. The areas of maximum intensification for those cyclones have been obtained and the existence of preferential zones of intensification has been verified. Finally a first sight of those cases has allowed to initiate the check up of the ability of the ERA-40 re-analyses for reproducing these intense Mediterranean storms.

1 Introduction

One of the objectives of the first phase of the WWRP WMO MEDEX project (medex.inm.uib.es) has consisted in the study of the Mediterranean cyclones from a climatological point of view. In order to reach this goal, a procedure for objectively detecting and tracking the cyclones was developed at the CMT of the Balearic Islands of the INM of Spain. The first version of the algorithm was applied on mean sea level pressure (mslp) operational objective analyses of HIRLAM-INM-0.5°. The details of the procedure itself and the statistical results, referred to the Western Mediterranean basin, can be found in Picornell et al. (2001). Some changes were then introduced in the algorithm for improving the detection and characterization of the cyclones, by one hand, and for extending the domain of application to the Eastern Mediterranean, by the other (Gil et al., 2003a). Afterwards, the extension of the procedure from msl to higher levels in the troposphere was considered and repeatedly applied, both

on HIRLAM-0.5° (Campins et al., 2006) and on ECMWF operational analyses (not yet published) in order to dispose of a more complete 3-D description of the cyclones. The resulting databases of cyclones are different in which the respective areas and the periods of time concern. The Western database (based on HIRLAM analyses) extends from June 1995 until May 2004. The entire Mediterranean one is referred to the June 1998–May 2004 period. Both two of them were obtained on a 0.5° lat/lon grid (~50 km, at the latitude of the Mediterranean) and they have been included in the MEDEX web (medex.inm.uib.es).

However the differences about the areas and time periods, the repeated application of the same algorithm on two different analysis systems can allow the intercomparison of the statistical results (in the common area and in the common period of time) and, hence, to test out the respective abilities of the analyses for describing the characteristics of the cyclones. At the moment, only a first approach to this comparison has been realised by Gil et al. (2003b) and only referred to msl cyclones. This point would acquire more relevance by considering that the above mentioned studies cover no more than nine years in time, but also that their results are clearly dependent of the changes introduced along the time in both operational systems.

The implementation of the algorithm on ECMWF ERA40 re-analysis system (Uppala et al., 2004) was the next step for obtaining a “true” climatology of cyclones for the Mediterranean as it was specified in Gil et al. (2003a) and Gil et al. (2002). The ERA40 re-analysis constitutes a large series of analyses and it allows to exclude the biases often introduced with changes to the model or the assimilation system in an operational system (Bengtsson et al., 2004).

When the algorithm's implementation was planned on ERA40 re-analysis, one of the reticences that were argued in spite of it was the resolution of the analyses for the correct representation of the cyclones that occurred in this area of the world. Some of the handicaps that must be overcome for objectively monitoring the cyclones in the Mediterranean are related to the size and the spectrum of scales that such kind of systems present. Generally speaking, due to the presence of the surrounding orography (actually the land areas),

Table 1. Most intense cases of cyclones obtained from the climatology based on ERA-40 analyses

Episode	Maximum development	Max. Circ. (GCU)
11–13 December 1967	12 at 06:00 UTC	16.53
10–12 January 1987	11 at 06:00 UTC	14.74
20–27 January 1981	21 at 12:00 UTC	13.77
13–16 March 1962	14 at 18:00 UTC	13.41
1–2 December 1969	01 at 18:00 UTC	13.11
27 February - 2 March 1958	01 at 00:00 UTC	13.05
10–12 November 2001	11 at 06:00 UTC	12.83
21–22 December 1979	22 at 00:00 UTC	12.12

they are smaller than the big cyclones in other maritime baroclinic areas in the world, like those in the Atlantic and the Pacific. Moreover, they usually have less than 48 h life-cycles and tracks not greater than 900 km, so their characteristics and monitoring are easily masked or not finely described when a large scale tracking algorithm is considered. The ERA-40 system is based on a 3-D-Var data assimilation and the use of T159 (~ 125 km) horizontal resolution (Uppala et al., 2004), and the tracking algorithm has been applied on a 1.125° lat/lon grid.

The initial purpose of this work consisted in testing the ability of the ERA40 assimilation system and the tracking procedure itself to correctly reproduce a selection of cases related to the presence of high impact weather. By doing that the MEDEX project would have a reference of case studies from a homogeneous system in order to compare the results obtained from some other numerical models. At the moment, only a first sight about the representation of some observed features for the most intense storms has been studied. A deeper diagnosis of these and some other (sub-synoptic) cases is left for some future work.

Thus, this paper is organised as follows. First of all, the most intense storms are selected from a criterion based on the value of the circulation for the msl cyclones. A brief sight about the zones of maximum intensification for these storms follows in order to seek the preferential areas of development. Afterwards some references about the occurrence of these cases have been looked for in old literature in order to verify the description that ERA40 makes of these cases. The first conclusions and further remarks finish the study.

2 Selection of cases

When the procedure was designed the circulation of the cyclone was chosen as a measure of its intensity each time it would be detected. The reasons for using this parameter in front of any other (like the mslp or the vorticity) as a measure of the cyclone strength were detailed and referenced in Picornell et al. (2001) and Campins et al. (2006), and coincident with those argued by Sinclair (1997). The circulation combines local values of the vorticity and the size of the cyclone,

and hence, it can be considered an appropriate parameter for characterising the cyclones' intensity.

At the algorithm, the geostrophic circulation of the cyclones is assessed by means of the expression

$$C = \int_A \zeta_g \cdot dA \quad (1)$$

being ζ_g the geostrophic vorticity and A the domain of the cyclone. The reader is referred to Picornell et al. (2001) and Campins et al. (2006) for the details about the definition of both the domain and the circulation of the cyclone from the algorithm.

The circulation is computed every time and at all levels for which the cyclonic centre is detected. By this way, the geostrophic circulation of the msl cyclone is one of the parameters that characterises the cyclone along its life cycle and allows its monitoring in terms of its intensity. The selection of the most intense cases from the database of cyclones is then reduced to the selection of cases that present the greatest circulation. Once the moment of maximum circulation has been detected it is immediate to reproduce the life of the cyclone. The geostrophic circulation values are $\sim 10^7 \text{ m}^2 \text{ s}^{-1}$ order of magnitude. Hereafter, it will be expressed in Geostrophic Circulation Units, being $1 \text{ GCU} = 10^7 \text{ m}^2 \text{ s}^{-1}$.

The maximum of the circulation's probability density function (not shown) is located around 3 GCU. The 90% of the cyclones have values of circulation below 6 GCU and 7 GCU, respectively, in the western and eastern Mediterranean, when only the moments of maximum development of the cyclones are considered. For this study and, in a first stage, the cases with circulation greater than 13 GCU at msl at any moment of its life-cycle have been selected. This circulation value corresponds to the 0.03% of the distribution and only 6 cyclonic events overcome this threshold. These numbers indicates the relatively extreme events considered. Two additional events, each of them showing a circulation greater than 12 GCU (that corresponds to the 0.08% of the distribution), have also been included in this selection due to the reasons below detailed. The final selection of cases is shown in Table 1. In the table, the moment in which the pressure reaches its minimum value for each cyclone and the maximum value of its circulation are also included.

The Table 1 shows that most of the cyclones occurred in winter or late autumn and only two of them have been detected in March. Two of these events, the 1958 and 1969 cases, have not yet been related to high impact weather phenomena (no documentation has been found at the moment of writing this paper). The other six correspond to extreme cyclogenesis cases that were, at that time, responsible of extreme weather events at different places of the Mediterranean countries. The 1967 and 1962 storms produced some of the most severe bora events documented in Croatia. In these dates there were, respectively, historic wind records at Senj and Split (Vucetić, 1997). Moreover, the 1962 was labelled as the strongest and longest-lasting severe bora event in Split (it would be probably overcome nowadays by a very strong event occurred in 2004 (Horvarth et al., 2005)).

The cyclone of 1987 corresponds to a low initially at the SW of the Iberian peninsula that evolves in a deep storm when it arrives to the Mediterranean. Associated strong wind gusts and heavy rain quantities were recorded at the Balearics. Afterwards the system explosively develops at the Tyrrhenian sea producing gale force winds at the Central Mediterranean.

Only one of the cases, the 1981 event, corresponds to a Genoa cyclone. In fact, this is not strictly speaking a classical orographic alpine event, but it is a case in which the Alps made an enhancement effect in an explosive cyclogenesis event.

The November 2001 and December 1979 cases are the lonely ones of the selection with values of maximum circulation lesser than 13 GCU. Nevertheless, the November 2001 storm is the 7th in the intensity ranking in terms of circulation, while the 1979 case occupies the 22th place. The reason why the last one has been included in this selection is that it has been recently documented and diagnosed by means of a modern high resolution NWP model like HIRLAM (Homar et al., 2002) and applying the today available state-of-the-art of the Mediterranean cyclogenesis. Both of them have a similar African origin, although the November case shows a more explosive and rapid development. And both of them are high impact weather events, especially the November 2001 case, with historical records in the island of Mallorca (Genovés and Jansà, 2003) and Algiers (Hamadache et al., 2003). Moreover, the catastrophic effects of this hurricane-like case (776 dead and 126 missing in Algeria) make of this event a reference case of last years, well documented by means of modern observation systems and current high resolution NWP models. These facts can help in the verification of the event from the ERA-40.

3 Areas of intensification. Tracks

The track for each cyclone centre has been computed and some similarities have been found in the geographical areas where they reach their maximum development. The results are resumed in Fig. 1 where, for each cyclone, the position every 6 h is represented. The last position for everyone corresponds to the maximum development time, that is, when the minimum pressure is reached. The maximum intensity is shown by a circumference whose radius is proportional to the circulation at that moment.

Some features can be emphasized in relation to the figure. Firstly, three regions of maximum development are observed. The most relevant one is the central Tyrrhenian sea and the south of Sardinia area, where four of the eight systems here considered reach their maximum development. Another region in the Central Mediterranean, south of Sicily and South of mainland Italy, is also clearly important in what intensification refers. In fact, two of the lows (the 1981 and 1962 cases) reach their respective minimum pressure at the same grid point. The presence of two circumferences for the 1962 storm shows the fact that it reaches twice its minimum pres-

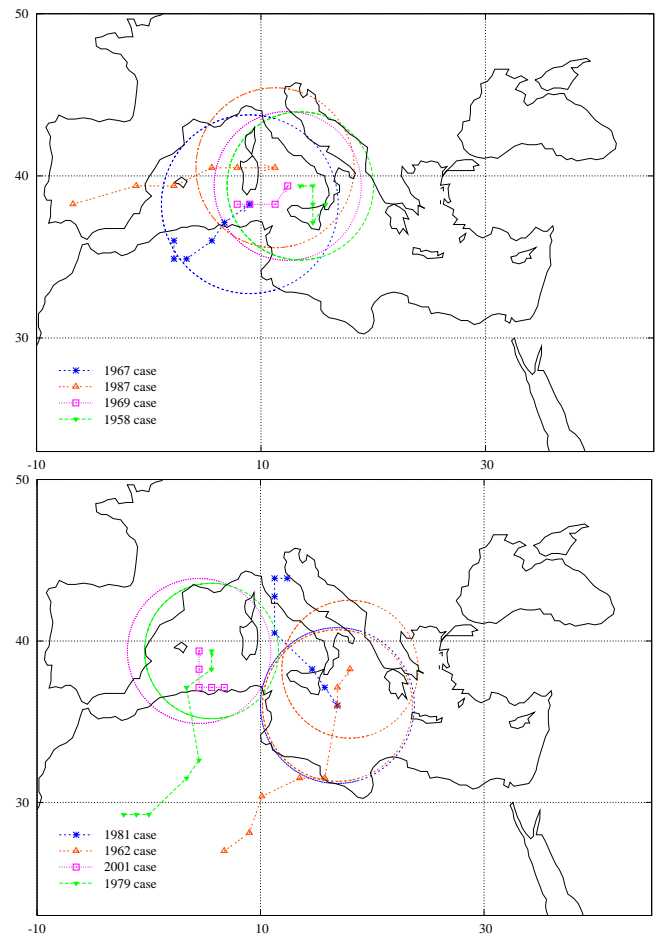


Fig. 1. Tracks of all the cases from their first detection until their respective maximum developments. The circumferences are proportional to circulation, according to Table 1.

sure (982.8 and 982.7 hPa, the 14 March at 18:00 UTC and the 15 March at 06:00 UTC, respectively), due to the arrival to the area of a northern upper PV anomaly that re-activates the system. Finally, the Balearics zone is, for these selected storms, the third region of maximum intensification. This is due to the presence of two events in the area. Only one of them (the 2001 case) deserves to be in this selection attending to the circulation criterion, as it has been explained above. The 1979 case being intense is not the 8th in terms of circulation.

These results are in accordance to some previous climatological studies. Sanders and Gyakum (1980) defined a “bomb” as an extratropical surface cyclone whose central pressure decreases at a rate of at least 1 bergeron= $1 \text{ hPa} \times \text{h}^{-1}$ for 24 h at a latitude of 60° N . For any other latitude, ϕ , the begeron is defined by a geostrophically equivalent rate, obtained by multiplying that by a factor $\sin \phi / \sin 60$. In the Mediterranean, the critical value of 1 bergeron varies from 20 hPa in 24 h at 45° N to 14 hPa in 24 h at 30° N . In a climatology about meteorological bombs, referred to the Mediterranean, for the 1965–1984 period (Conte, 1985) and, afterwards extended until 1995, Conte et al. (1997) identified the

Table 2. Comparative of intensification rates and position of the centres of the cyclones between climatological results and ERA40 monitoring of Mediterranean “bombs”.

Date	Conte (1964–1984)		ERA40 (1957–2002)	
	Int.(bg)	Position	Int.(bg)	Position
12/12/1967	1.29	8 E/37 N	0.92	9 E/38 N
21/01/1981	1.65	15 E/38 N	1.35	15 E/37 N
22/12/1979	1.41	7 E/41 N	1.13	5.6 E/39 N

Tyrrhenian, the central-south Adriatic and the northern Ionian, and a third region including the Aegean sea, like the regions where the explosive development preferentially occurs. In those works, the Western Mediterranean basin around the Balearics is also a minor (in number of cases) but preferential zone of explosive development (Fig. 1 of Conte et al. (1997)).

The absence of cases in the Eastern Mediterranean and the Adriatic in this paper can be emphasized. The reason for that is related to the restricted number of cases here considered, that is, none of the cyclones in those areas overcome the 13 GCU of circulation. This would be probably related to the size of those weather systems. The criterion here used for selecting the cases is based on circulation values that are directly dependent on the area (domain) of the cyclone. In closed zones like the Aegean sea and the Adriatic, rounded by mountains, the systems are smaller than in the Central Mediterranean what is reflected in the value of the circulation and hence in their absolute intensity.

One more thing must be commented in relation to the Fig. 1. Three of the eight cases reflect a North-African origin. In fact, this influence can be extended to the November 2001 case, that initially developed as a secondary little system in the sea, from a large scale one in North-Africa (Genovés and Jansà, 2003) and ERA40 also reflects (see Fig. 1). This common north-african origin could be of relevance for future observation campaigns.

4 Comparison of intensification rates and position of the cyclone’s centres with old studies

In a first stage, the ability of the ERA40 for correctly representing these intense Mediterranean storms has been checked by means of the comparison of the description from ERA40 with the existent data and/or old references relating these cases. No verification has been made, at the moment of writing this paper, in front of observations for all of the cases.

In Conte (1985) the complete calendar of meteorological bombs for the period 1964–1984 was published. Except for the 1969 case, all the intense cyclogenesis events included in Table 1, and occurred between 1964 and 1984, appeared in that calendar. The 1969 event is a case of rapid and short development that shows a decrease in the pressure for only 18 h, and probably it was considered like an intense case, not a bomb. In the Conte’s list, the date of maximum

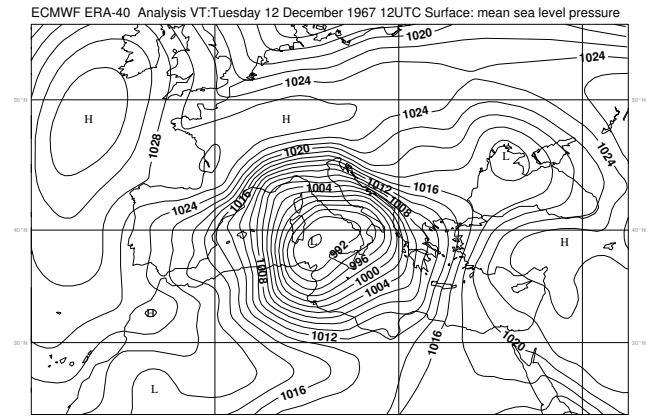


Fig. 2. MSLP Analysis 12/12/1967 at 12:00 UTC.

deepening, the intensity in bergeron (corrected in latitude), the geographical position of the “bomb” in the moment of its maximum deepening and the mechanism of development (Conte et al., 1997) were included as parameters for characterising those systems. Their values (except those related to the mechanism of development) have been assessed for the correspondent events in ERA40 reanalyses. The results are resumed in Table 2.

From the table, some differences can be observed regarding the intensification rates and the position of the low centres. First of all, the intensification rates assessed from the ERA40 analyses are clearly lesser than those from Conte. This could indicate an underestimation of the pressure at the centre of the cyclones in the analyses. One example of this possible underestimation can be observed in Fig. 2 where the mslp analysis for 12 December 1967 at 12:00 UTC is presented. It can be observed that surrounding the center of the cyclone the pressure gradient is stopped in front of the almost uniformly distributed gradient that would be expected at the sea surface where no obstacles are found for producing a deformation in the isobars.

According to the Table 2, the relative differences in the intensification rates are around 80% of those found by Conte. It is not clear how were the intensification rates assessed by Conte, although they were done from analyses of different Bulletins of the time belonging to National Meteorological Services. This behaviour has also been observed for one more case, the 2001 case, obviously not included in Table 2. Figure 3 shows the pressure record at Palma’s CMT compared to the evolution of the mslp from ERA40 at 2.6 E, 39.5 N point, coincident to the CMT coordinates.

The pressure evolution is well caught by ERA40 analysis: the little fluctuations in the pressure record are also reflected in the analysis. Only the final sudden decrease of the pressure is underestimated in a 20% of the real value. In fact, this sudden decrease is of a time scale of 1.5 h and, thus, not exactly comparable to the temporal resolution of ERA-40 analysis (6 h). It must be noted that the centre of the cyclone for this event didn’t pass exactly over Palma, but close to it. In fact, this record is the closest available to the centre of the cyclone.

This recent event, deepened on the sea and although many studies have been developed on it, it is also under study, due to the complexity that the atmospheric situation presented.

Returning to Table 2, some discrepancies are also observed in the position of the cyclone centre at the moment of maximum development when comparing the results from ERA40 to those of Conte. The discrepancies appear for the three cases but they are greater for the 1979 case. In the analysis, the cyclone reaches its minimum pressure on 22 December 1979 at 00:00 UTC, at 5.6 E/39 N. Six hours later, at 06:00 UTC, the centre of the cyclone is placed at 6.75 E/41.6 N, practically coincident with the position assigned by Conte. Less reliable seems the evolution of the pressure at the centre of the cyclone. The pressure decreases abruptly until 6 h before the minimum pressure is reached. In the last 6 h of development the pressure decreases only 0.5 hPa. For twelve hours the behaviour of the pressure is almost constant.

Homar et al. (2002) concluded that the latent heat release from the condensation processes throughout the troposphere was responsible for the 45% (7 hPa) of the total deepening of the 1979 cyclone. They arrived to this conclusion by means of numerical experimentation and from the analysis of a warm core present just west of an upper PV anomaly in Fig. 13 of Homar et al. (2002). The warm core and the eastern PV anomaly they studied are also present in ERA-40 analysis, like the Fig. 4 shows. Thus, in spite of the discrepancies related to the intensification or the position of the centre of the cyclone, the ERA-40 analysis is able to reproduce this feature.

5 Conclusions

From the implementation of a procedure for detecting and tracking the cyclones on ERA40 re-analyses, the detection of the most intense storms occurred in the Mediterranean for the last 45 years has been possible. The definition of intensity has been based on the value of the circulation for the cyclones every time they were detected. The most intense cyclones have then been defined as those with the highest values of circulation. The criterion for the selection has imposed restrictions about the size of the system so the study has been restricted at the moment to synoptic scale cyclones. More investigation must be done for the treatment that ERA-40 makes of some sub-synoptic systems related to high impact weather.

Most of these intense storms occurred in winter or late autumn. Only two of them have been detected in late February and March. Some of them were related to historical events of high impact weather in different Mediterranean countries, although more documentation would be necessary for a complete diagnosis of the cases.

The tracks of the cyclones have been computed and some common areas of maximum development have been detected. The central Tyrrhenian sea including the south of Sardinia is the area where the major concentration of cy-

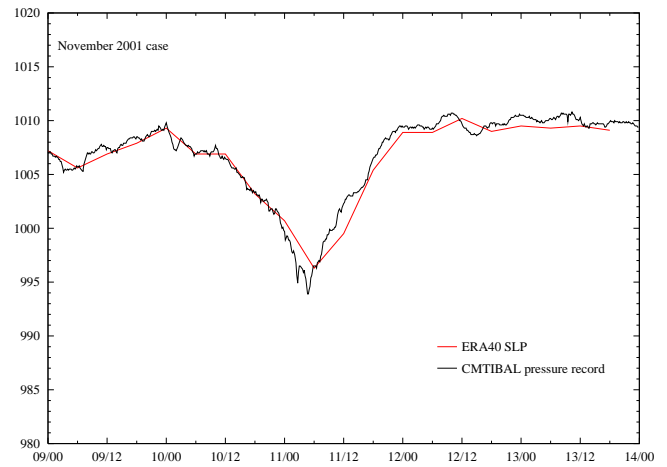


Fig. 3. Pressure record at CMT in Palma de Mallorca and ERA-40 mslp analysis for 10–12 November 2001 at point of coordinates 2.6 E, 39.5 N.

clones explosively developed. The Ionian sea and the area around the Balearic Islands are the two other zones where the cyclones reach their respective maximum developments. These results corroborate some previous climatological studies about explosive developments in the Mediterranean. Although the same studies point to other additional areas as important for explosive developments, the restricted number of cases considered in this paper and the size of the weather systems produced there, more conditioned by orography, are probably the reasons because no system of those areas is between those with the highest circulation values.

Four of the eight cyclones detected are of North-African origin what would be taken in consideration for future observation campaigns affecting the Mediterranean weather systems.

All the eight systems here considered reached the maximum intensity over the sea.

Some discrepancies have been detected in the intensification rates of the pressure at the centre of the cyclones and also in their position at the moment of maximum development when comparing the analyses of ERA-40 with the results of previous studies about explosive cyclogenesis in the Mediterranean. The disagreement about intensification could be due to the resolution and/or to the treatment of the assimilated observations in ERA-40 system. The importance of heat and moisture fluxes in the deepening of the systems especially in the sea and in cloudy areas with a great lack of conventional observations makes especially relevant the information obtained from satellite data. However more investigation is needed to confirm these statements.

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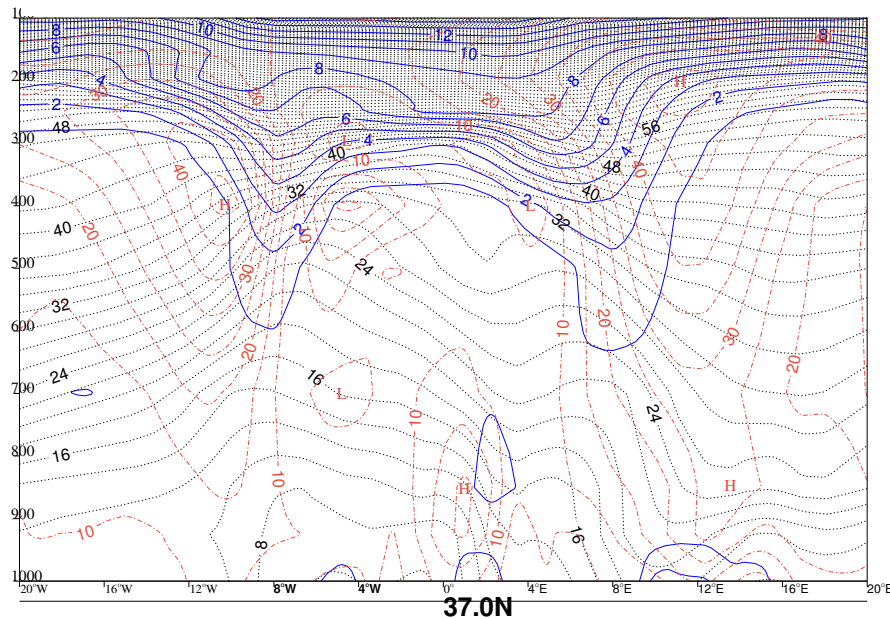


Fig. 4. PV (blue lines), wind (brown lines) and potential temperature (dashed lines) cross section across the cyclone centre, December 21, 1979, at 18 UTC from ERA-40 analysis. PV contouring interval, 1 PVU. Wind countouring interval, 5 m/s. Potential temperature contouring interval, 2°C.

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